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STRUCTURE OF AN AUTOMATED SYSTEM FOR THE CALCULATION OF ANNEALING REGIMES FOR GLASS ARTICLES

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The factors needed to identify an optimum energy-saving annealing regime for glass articles are considered. A structure of an automated system for the calculation of glass annealing conditions is proposed, which makes it possible to model and optimize the process of annealing of sheet, container, and household glass.

In manufacturing glass one has to implement annealing of glass articles that have different chemical compositions (and, consequently, different properties) and different geometrical shapes and sizes on the same equipment. As a result, an annealing regime in the furnace is set with a substantial safety factor. Such a universal annealing regime is suitable for a wide range of products but is not cost-effective. It is much more efficient with respect to energy savings and maintaining a required quality level (which depends on the level of residual stress in a glass article) to implement an annealing regime developed specifically for a particular type of glass, which could be readjusted when the product range changes.

For this purpose it is essential to be able to model the annealing process, which implies the possibility of reproducing the thermal prehistory and regularity of formation and relaxation of stresses in a glass article based on the chemical composition of the glass, the geometrical shape and size of the article, the velocity of its motion, the annealing furnace parameters, the experimental temperature dependence of relative elongation or viscosity of the glass sample, the spectral absorption of the glass in different wavelength intervals, and a preset temperature-time annealing regime. The development of this series of models (an automated calculation system) contributes to solving an important problem: identifying an optimum annealing regime, which ensures a minimum energy consumption in annealing or minimum residual stresses in a glass article.

The structure of an automated system for calculation of annealing conditions for glass articles can be based on one of the most essential systematic principles, namely, the module-structure principle that implies identifying groups of system elements, which are described only by input and output data and have a certain integrity, and regarding the system as a set of these modules. Thus, instead of considering a part of the system, one considers a set of its input and output effects, which are means of conjunction of individual modules. Dividing a system into modules is a convenient and common technique making it possible in principle to analyze infinitely complex systems, since by characterizing a group of elements only by their input and output data, it becomes possible to operate this part of the system, regardless of how its elements are interrelated and how they interact.

To model temperature fields either by analytical or by numerical methods, one should know such thermophysical properties of glass as the thermal conductivity λ and the temperature conductivity a. The latter is usually found from the following formula:

$$a = \frac{\lambda}{\rho c};$$

consequently, we need the values of the density ρ and the specific heat c of glass, without which the problem of radiation heat transfer cannot be solved either. Furthermore, to calculate radiation heat transfer inside glass, one should also know the value of an optical property, i.e., the refractive coefficient n.

To model the stress field, one should have values of such mechanical properties of the glass as the Young modulus E and the Poisson coefficient μ as well as the photoelectric constant (the Brewster constant or optical stress coefficient) k to convert stresses measured in the standard measurement

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system (N/m^2) to the system accepted in the glass industry (nm/cm).

It is obvious that to model temperature and stress fields in glass articles, one should be able to calculate values of the specified thermophysical, mechanical, and optical properties of glass for any temperature. The most convenient way is to determine these values from the chemical composition of the glass, since it is always known and required oxide contents are maintained with a high degree of accuracy in preparing batches.

Consequently, the first two modules of the system have to be as follows: "*Input of the chemical composition of the glass*" and "*Calculation of the thermophysical, mechanical, and optical properties of the glass from its chemical composition.*"

As glass articles subjected to annealing can have either flat or cylindrical shape, an obligatory component of the system for calculation of the annealing condition should be "*Input of the geometrical shape and size of a glass article.*"

For a glass band, the required geometrical sizes are thickness L and width B; for a cylindrical tumbler they are height H, bottom thickness H_2, inner R_1 and outer R_2 radii; for a bottle: height H, bottom thickness H_2, height of the lateral part H_1 and the neck H_4, the inner and outer radii of the main part (R_1, R_2) and the neck part (R_3, R_4).

The main parameters of the annealing furnace are also very essential in calculating the annealing of articles: geometrical parameters — furnace height H_f, furnace width B_f, number of annealing zones N_{an}; velocity of motion of the article inside the furnace v_{art}; the maximum possible heating rate $R_{H_{max}}$ and cooling rate $R_{C_{max}}$ ensuing from the design specifics of the furnace. Furthermore, for household glassware it is necessary to know the velocity of the conveyor belt from the molding machine to the furnace v_m, the number of articles across the furnace width N_{art}, and the distance between them S. We propose that the temperatures of thermocouples and the medium in different zones would be accounted for in another module ("*Identifying heat-exchange conditions in annealing*"), which considers in more detail the temperature–time conditions of annealing. Heat exchange in annealing furnaces can proceed by convection only, by radiation only, or as combined radiative-convective heat exchange. Convective heat exchange with glass articles is usually implemented in transmitting or absorbing heat by moving air, and radiation heat exchange is implemented by radiation from heater elements deliberately inserted in the roof and the bottom of the annealing furnace. Accordingly, annealing furnaces can be convective, radiative, or convective-radiative, and the next module of the system is evidently "*Input of the type and main parameters of the annealing furnace*."

To calculate temperature–time variations of glass properties under heat treatment (relaxation of the structure of the glass-forming material) and subsequently calculate stresses, it is necessary to have an experimental temperature dependence of at least one glass property (relative elongation or viscosity of the sample). It should be mentioned that virtually every glass factory has a dilatometer, i.e., a device for recording a dilatometric curve (dependence of relative elongation of a sample on temperature), whereas only research and development centers own viscometers. Accordingly, it is possible to process experimental data of dilatometric measurements while calculating viscosity based on the chemical composition using the known Helhof and Okhotin methods. This helps to identify two other modules of the system: "*Processing experimental data of dilatometric studies*" and "*Calculation of the temperature dependence of glass viscosity based on the chemical composition of the glass.*"

The module "*Processing experimental dilatometric data*" makes it possible to calculate instant values of the TCLE α_i for any temperature, and use of the relative elongation $(\Delta l/l)_i$ and the point of the temperature dependence of viscosity $\log \eta_j$ enables one to determine the relaxation constants needed for calculation. The respective module will be called "*Calculation of structural relaxation constants.*"

Models for the calculation of temperature fields in glass articles can be divided into two main groups: "non-transparent," which do not take into account heat transfer by radiation inside the glass, assuming that all heat exchange by radiation occurs on the surface of the article, and "semitransparent," which take into account redistribution of heat for inner points due to heat exchange by radiation. Accordingly, the system should provide for the possibility of entering a dependence of the spectral absorption coefficient of the glass $\log \gamma_i$ on the radiation wavelength falling on this glass λ_j. The respective module is called "*Input of spectral properties of the glass.*"

After a mathematical model is developed, its adequacy ought to be verified. Concerning the model for the calculation of temperature fields in glass, this means that the model should allow for calculating the parameters of convective-radiative heat transfer (convective heat transfer coefficients α_1, α_2 and reduced degrees of blackness ε_{S_1}, ε_{S_2}) by means of correlating experimental and estimated values of temperatures for different points of the glass article (usually external points) and decreasing the spread between them to a prescribed value. This implies identification of heat-transfer parameters: determining their values which ensure convergence with a certain degree of precision between temperatures of surface points on the article calculated on the basis of the temperature-field model described above and experimental temperatures. Reproducing temperature variations at the surface points of the article with a preset degree of accuracy makes it possible to adequately describe temperature distribution inside the glass as well. In view of the different conditions of heat transfer for an article transported from the molding machine to the annealing furnace (pre-annealing period) and an article inside the furnace (annealing period), the need for two more modules becomes evident: "*Identification*

of heat-transfer conditions before annealing" and "*Identification of heat-transfer conditions during annealing.*"

The most important moment in calculation of annealing regimes is the development of a mathematical model for the calculation of a temperature field and for formation and relaxation of stresses in glass articles of various shapes. The overwhelming majority of papers and books on heat-conduction theory and calculation of temperature fields are dedicated to sheet glass. It is proposed to calculate temperature fields in cylindrical glass articles using the model of a temperature field in a glass band, in which the band thickness is replaced by what is known as the "effective thickness" of articles. In this case, calculation is significantly less accurate, especially due to complex heat-transfer conditions for articles placed in rows on a conveyor grid of the annealing furnace. Accordingly, for successful functioning of an automated system for calculation of annealing, it is necessary to develop original numerical methods for calculation of the temperature field in cylindrical glass articles, considering mutual heat exchange by radiation between the articles in a technological flow [1].

Furthermore, most traditional models for calculation of temperature distributions in a glass band do not take into account the heterogeneity of the initial temperature distribution, the asymmetry of heat-exchange conditions on the lower and upper surfaces of the band, the dependence of thermophysical properties of the glass on temperature, heat transfer by radiation in general and inside the glass in particular, and the dependence of the glass-absorption coefficient on the radiation wavelength. Thus, it is necessary to develop models for calculation of a temperature field in sheet glass for the most general case of asymmetrical convective-radiative heat exchange [1].

With respect to the calculation of relaxation of the structure and stresses in glass articles, the situation is better. The majority of variants for calculating temperature-time dependences of properties of glass-forming compounds and stress fields in glass articles are based on the Tul – Narayanaswamy relaxation model, which during the past decade has proved its adequacy in describing heat-treatment processes in glass. The best known variant is the algorithm of the Leningrad Institute of Chemistry of Silicates (called the IKhS algorithm) [2, 3]. However, the mathematical model for calculation of relaxation of the structure and the stress field in a glass band based on the principal relationships of the IKhS algorithm should be extrapolated to glass articles of a cylindrical shape taking into account splitting of the glass article into several calculation zones and considering the two-dimensionality of the problem [1].

Thus, the module which uses mathematical models for calculation of temperature and stress fields in glass articles is named: "*Calculation of temperature and stress fields in glass for an existing annealing regime.*"

The last module of the system, which implements its main practical function, is "*Calculation of an optimum annealing regime.*"

The method for calculation of an optimum regime of cooling of glass articles considered in [4] is extended to the general case of heat treatment of glass, including the stages of its heating, exposure, and cooling.

Thus, the automated system for the calculation of glass annealing regimes described here makes it possible to model and optimize the process of annealing of sheet, container, and household glass. It can also be used for the calculation of other processes of heat treatment of glass, for instance, hardening.

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